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# Synthesis of Ultrathin ta-C Films by Twist-Filtered Cathodic Arc Carbon Plasmas

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## ABSTRACT

The application of cathodic-arc-deposited films has been very slow due to the infamous macroparticle problem. We report about the application of the open Twist Filter as the key component to an advanced filtered cathodic arc system. Ultrathin tetrahedral amorphous carbon (ta-C) films have been deposited on 6 inch wafers. Film properties have been investigated with respect to application in the magnetic data storage industry. Films can be deposited in a reproducible manner where film thickness control relies on arc pulse counting once deposition rates have been calibrated. Films of 3 nm thickness have been deposited that passed acid and Battelle corrosion tests. Monte Carlo Simulation of energetic carbon deposition shows the formation of an intermixed transition layer of about 1 nm. The simulation indicates that because the displacement energy of carbon is not smaller than of magnetic materials, films thinner than 2 nm are either not high in $sp^3$ content or represent a carbidic phase, i.e. contain substrate material. The last finding is general and not limited to cathodic arc deposited ta-C films.

## INTRODUCTION

Diamondlike films are characterized by an outstanding combination of advantageous properties: they can be very hard, tough, super-smooth, chemically inert, well adherent to the substrate, and compatible with lubricants. They can be deposited fast, efficiently, at low cost, and on room temperature substrates. The various deposition methods result in a variety of diamondlike films. Widely used is hydrogenated diamondlike carbon (DLC or a-C:H), nitrogen-doped amorphous carbon (a-C:N) or amorphous carbon nitride ($CN_x$) [1-3], hydrogenated carbon nitride ($CH_xN_y$), non-hydrogenated amorphous carbon (a-C), silicon-doped amorphous carbon (a-C:Si) or silicon carbide (SiC) [4], and metal-doped amorphous carbon (a-C:Me) [5]. Amorphous carbon films (a-C) often have a very high percentage of tetrahedral ($sp^3$) bonding and therefore they are referred to as tetrahedral amorphous carbon (ta-C).

Ultrathin (< 5 nm) hard carbon films are being used as protective overcoats on hard disks and read-write heads. The tribological properties of the head-disk interface are not only mechanical but also chemical in nature: the overcoat is required to protect the magnetic layer against wear and corrosion [6, 7]. As the areal density (of information stored) increases at a breathtaking rate of about 100% per year [8], the "magnetic spacing" between the magnetic layer of the disk and read/write sensor of the head must decrease. The magnetic spacing includes magnetically dead layers, carbon overcoats, lubrication, pole tip recession, and the fly height. Thinner overcoats allow the head to be closer to the disk, and hence, the size of individual bits to be smaller. Areal densities of 70 Gbit/in$^2$ have recently been demonstrated in the laboratory, and the industry is working toward 100 Gbits/in$^2$. The magnetic spacing approaches the sub-10-nm regime and overcoat thickness must shrink to 1-2 nm. Overcoats currently used are sputtered or ion-beam deposited diamondlike carbon films, typically doped with hydrogen or nitrogen. They cease to provide acceptable levels of corrosion protection and wear resistance for films thinner than 4 nm.

The challenge of ultrathin film synthesis is to make the films as thin as possible and still continuous, as opposed to an assembly of islands. There are large variations even within each class of materials, depending on the method and parameters of deposition.

Tribological properties and fracture toughness of ultrathin amorphous carbon coatings (hydrogenated and non-hydrogenated) deposited by different deposition techniques have been compared. Films synthesized by filtered cathodic arc deposition were shown to exhibit good properties even at very small film thickness [9, 10].

Non-hydrogenated tetrahedral amorphous carbon films, ta-C, can be synthesized by argon sputter deposition using a graphite target, by pulsed laser ablation of graphite, by mass-selected ion beam deposition of $C^+$, or by cathodic arc plasma deposition. The latter can be performed in continuous or pulsed mode. Pulsed filtered cathodic arc plasma deposition has been identified as a promising technique [11]. The greatest challenge is the complete removal of "macroparticles" that are generated at the cathode spot. In this paper, we focus on pulsed filtered cathodic plasma deposition of ta-C films and report about the progress made towards the synthesis of high-quality, ultrathin films suitable for application in the magnetic storage industry.

## CATHODIC ARC CARBON PLASMA

Generally, cathodic arc plasmas are fully ionized, often with multiply charged ions present [12]. Cathodic arc carbon plasma is in some respect an exception because the ion charge state is only 1+. However there are a few percent of 2+ at the beginning of each arc pulse [13]. The plasma ions move with supersonic velocity of about Mach number 5, corresponding to kinetic carbon ion energy of about 54 eV [14]. This recent result indicates that the carbon ion energy can be significantly higher than the about 20 eV that is usually quoted [15]. It is known that the ion energy is critical for the properties of ta-C films such as $sp^3$ content, hardness, Young's modulus, density, and stress (see, for instance, [16]). Very recent (still unpublished) results indicate that the ion energy can further be manipulated for instance with magnetic fields, and carbon ion energies exceeding 100 eV can be achieved without biasing the substrate.

The formation of carbon plasma is unusual for those who are not familiar with cathodic arc plasmas. The arc current, typically 100 A or more, is concentrated at the cathode surface in micron-size cathode spots, i.e. cathode spots are locations of extreme current density. Because most of the voltage drop (~ 20 Volts) is in the cathode fall, the power is concentrated at cathode spots. Power densities can reach $10^{13}$ W/m$^2$, leading to explosive transition of solid cathode material to the dense plasma state. This process of often called "arc evaporation" but one should keep in mind that plasma, not neutral vapor, is the result of the powerful phase transition. The dense carbon plasma has a very high pressure, exceeding atmospheric pressure by orders of magnitude, and it expands in the vacuum ambient.

Not only plasma is produced at cathode spots but also debris particles, usually referred to as "macroparticles." For carbon, large chunks of graphite (fractions of millimeters) are sometime ejected from the cathode – it is believed that shock-heated gas inclusions of the graphite cathode contribute to these massive cathode losses. However, smaller macroparticles are much more frequent, and their distribution extends well down into the nanoparticle range [17]. The presence of macroparticles is not acceptable for ta-C films in magnetic storage applications. Macroparticles could lead to crashes of the head as well as to pinholes and defects that will cause ta-C films to fail in corrosion tests.

## MACROPARTICLE FILTERS

A common approach to macroparticle removal is based on the vast mass-to-charge difference of macroparticles and plasma particles; see reviews [18-21]. The plasma can be guided out of the line-of-sight from the cathode using curved magnetic fields, employing combined magnetic and electric mechanisms for electrons and ions, respectively. The motion of macroparticles is almost independent of the presence of fields; thus they move along straight trajectories, thereby being separated from the plasma. This concept was originally introduced by Aksenov and coworkers in the late 1970s [22].

In the literature, two basic constructions and filter philosophies have been described. They can be labeled as closed and open filters. The "classic" 90° filter duct [22] employs a duct, i.e. a closed tube, surrounded by a set of magnetic field coils. The interior wall of the duct is equipped with baffles designed to catch or reflect macroparticles. Graphite particles may suffer multiple reflections, and may fracture into several "sub-macroparticles" [21]. Consequently, there is a significant likelihood that carbon macroparticles, or fractions of them, arrive at the substrate via multiple reflections. Additionally, small nanoparticles may be transported through momentum exchanged with ions ("ion wind"). There are a numerous *closed* filters derived from the classic 90° filter, including 45° filters [23], S-filters [24], segmented filters [25], filters of rectangular cross section [26, 27], and out-of-plane double-bent filters [28, 29].

In contrast to conventional closed filters, *open* filters address the issue of particle reflection by removing the particle from the filter and plasma volume via openings [30-32]. Figure 1 shows an S-shaped open filter that consists of a bent solenoid. It is obvious that most macroparticles can leave the plasma volume, and some are removed even if they hit a turn of the magnetic field coil.

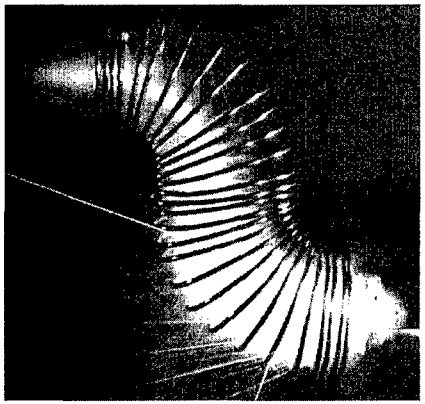

Figure 1 S-shaped open filter guiding carbon plasma from a cathodic arc plasma source (right) to the substrate region (left). Carbon macroparticles are hot and can therefore easily be identified by their bright traces. Open-shutter photograph, arc current 1000 A, pulse length 1 ms.

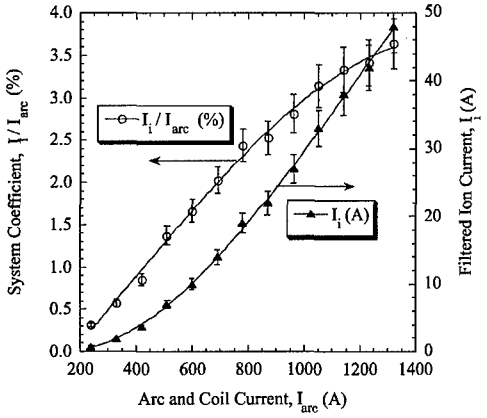


Fig. 2. Output of the Twist Filter prototype as described by the filtered ion current and the system coefficient. Arc and filter-coil are electrically in series.

## THE TWIST FILTER SYSTEM

A new open filter design was presented [33] that is essentially a "twisted" S-shaped open solenoid, or "Twist Filter." Twisting refers to a rotation of one bend of the S-filter with respect the other bend.

The design of the system is not a marginal improvement but based on paradigms derived from physical and empirical laws:

1. Plasma losses in filters scale exponentially with the filter path length [30]. Therefore, the filter must be short.
2. Because the filter path is short, its inner radius must be small to prevent a line-of-sight between filter entrance and exit.
3. The plasma source (specifically its cathode) must be small to match the size of the filter entrance, otherwise the plasma produced will not enter the filter.
4. If the cathode is small, it needs to be replenished e.g. via a cathode feed mechanism.
5. If the source and filter are small, heating constraints can be alleviated by operating in a pulsed mode. Pulsed mode could also be beneficial in addressing the "plasma wind" issue.
6. In pulsed mode, the high arc current can be used to generate a strong magnetic filter field that is in perfect synchronization with the plasma production.
7. Repetitively pulsed operation requires simple and very reliable arc initiation such as the "triggerless" mechanism [34]. This mechanism relies on the formation of plasma at a location where the cathode touches a conducting layer that is connected to the anode.
8. The macroparticles that have left the plasma volume must be prevented from reaching the substrate. Therefore, the system needs to have a macroparticle "firewall", i.e. a wall separating source and filter area from the clean substrate area.
9. The system needs to have a designated region in which macroparticles are collected for removal on a regular maintenance schedule. This area is located under the plasma source and filter.
10. The plasma exiting the filtered is highly focused but a uniform deposition over a relatively large area (e.g. wafer of 95 mm diameter) is required. Therefore, a plasma expansion zone and a plasma homogenizer are needed.
11. All parts of the system (source, filter, homogenizer, power supply, firewall, etc) need to be considered as a unit with well-matched parameters.

The Twist Filter system is a consequent realization of the design paradigms. The Twist Filter system consists of several matching components: the cathodic arc plasma source, the Twist Filter, the macroparticle "firewall," a plasma expansion zone, a plasma homogenizer, and a substrate positioning mechanism.

Arc plasma source, filter, and homogenizer are electrically in series and powered by a compact, rack-mounted pulse forming network (PFN) [35]. The cathode of the plasma source is a graphite rod of 6.25 mm diameter. The rod can be slowly and precisely advanced via a micrometer drive to compensate for the erosion at its front face. High arc current and small cathode area lead to uniform erosion of the cathode without spot steering or any other specific means of spot control. The anode is grounded while all other components are free of ground, thus their potentials are in reference to the anode. The anode itself is an open baffle structure made from copper; it serves as a pre-filter: A large fraction of macroparticles are already removed from the plasma when it enters the filter. The repetitively pulsed arcs are initiated by simply switching the high (open-circuit) supply voltage of 1 kV to anode and cathode; a conducting layer on the ceramic between anode and cathode lead to hot-spot and plasma

formation at the cathode. This "triggerless" mechanisms shows exceptional reliability [34]. The arc current is typically 1.5 kA with pulse duration of about 1 ms and a pulse repetition rate of 3 p.p.s. The duration of arc pulses is given by the PFN while all other parameters can easily be adjusted. The base pressure of the vacuum system is about 1 x $10^{-7}$ Torr but pressure increases during deposition to the $10^{-5}$ Torr region, presumably due to outgassing caused by heating of the filter and other components.

Due to the design of the Twist Filter [33], the likelihood of macroparticle transport is greatly reduced while the plasma transport is impressive compared to other filter designs. The filtered ion current may reach close to 4% of the arc current (Fig. 2). The ratio of filtered ion current to arc current can be named "system coefficient". For comparison, most filtered arc systems have a system coefficient of about 1%. It is important to realize that one not only needs to reduce macroparticles to a minimum but also maximize the plasma output because only the ratio of filtered plasma to residual macroparticles is what really matters.

The coil turns of the Twist-Filter have a flat cross-section promoting macroparticle reflection towards the outside of the filter volume, i.e., the coil represents a baffle structure (Fig. 3). The Twist Filter has a strong magnetic field (0.25 mT/A) providing excellent plasma confinement. At high currents (> 1 kA), not only electrons but also carbon ions are magnetized. The fringe field at the filter entrance is well suited for source-filter coupling.

The plasma at the exit of the Twist Filter is highly focussed. The streaming plasma expands on its way to the substrate. With special means, a deposited film will have a Gaussian thickness distribution with the thickest area in the center. A magnetic multipole, also known as a magnetic bucket, can be used to flatten the plasma density distribution. Magnetic multipoles can be made from strong permanent magnets or by using a wire structure as shown in Fig. 4. The homogenizer is located in the center between the filter exit and the substrate location.

## PERFORMANCE OF THE TWIST FILTER SYSTEM

The Twist Filter System operates with typically 1500 A arc current in 1 ms pulses, giving about 30 A of filtered carbon ion current during the pulse. As usual for pulsed systems, one has to distinguish between instantaneous and average values. The duty cycle is defined by $\delta = t_{on}/(t_{on} + t_{off})$. For instance, when using 3 pulses per second, the duty cycle is $3 \times 10^{-3}$ or 0.3%, thus the averaged ion current is 90 mA. This is comparable to the output of conventional filtered cathodic arcs that operate in continuous mode. This ion flux corresponds to about 150 pulses that are needed to deposit a 3 nm film on a 6 inch wafer. With 3 pulses per second, one would need a deposition time of about 50 s. Faster deposition is possible and has been demonstrated, but cooling of the filter becomes an issue that must be solved in a next generation system.

Film thickness and graphite cathode rod usage are very reproducible and can be predicted simply by counting arc pulses, provided that cathode advancement is periodically performed and controlled (e.g. every 1000 pulses). The pulse number – thickness relationship is about linear although we found that the output per pulse increases slightly and reproducibly during a deposition run. We attribute this to the increasing cathode temperature. The film thickness was measured by ellipsometry and calibrated by AFM step height measurements.

Film uniformity was a major issue since deviation from the targeted thickness are requested not to exceed 3% (however, one has to realize, that 3% of a nominal thickness of 3 nm is 0.09 nm, that is about half the average bond length between individual carbon atoms of ta-C!). For thicker films (> 10 nm) deposited with the Twist filter system, a uniformity of ±2% could be

achieved while ultrathin films showed somewhat larger non-uniformity. Since the plasma distribution should not depend on the pulse number, it is believed that the ellipsometric determination of film thickness for films under 5 nm is difficult, to say the least. To be complete we need to mention that the substrates were mounted on a rotating holder (20 rpm) and a typical pulse repetition rate was 3 p.p.s.

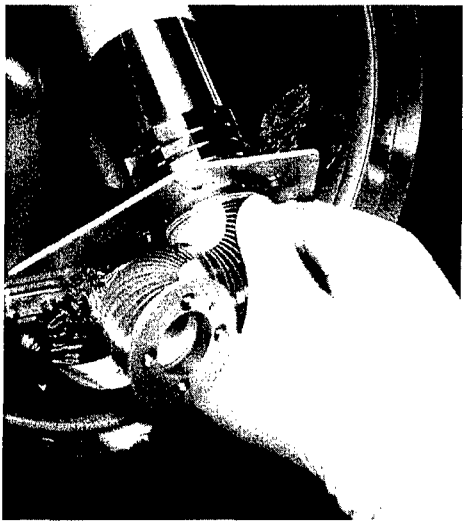

Figure 3. Mounting of the alpha-version Twist Filter to the plasma source. Note the compact size compared to the often 1-m long filters of dc filtered cathodic arcs.

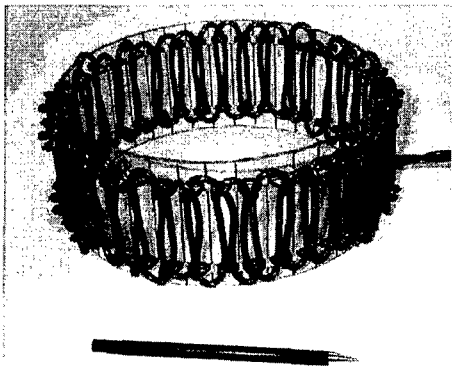

Figure 4. A simple electromagnetic multipole or "bucket" used to flatten the plasma density distribution in the alpha-version of the Twist Filter System. As with the Twist Filter, the arc current itself (usually 1.5 kA, pulsed) were used to generate the magnetic field. The pen is for size comparison.

## PROPERTIES OF ta-C OBTAINED BY THE TWIST FILTER SYSTEM

### Corrosion resistance

Corrosion resistance is the key property of ta-C films for 100 Gbit/in$^2$. When a film thickness is approached that is better described by the number of atoms than nanometers, some properties such as hardness become very difficult to measure or even ill-defined. However, the requirement of corrosion protection of the magnetic layers remains.

Preliminary measurements of ultrathin films obtained by using a prototype S-filter and Twist Filter have been reported elsewhere [36, 37]. Two major steps were done recently: one was the development of an alpha-version Twist Filter system, and the other was its installation in a class 100 cleanroom at Read-Rite corporation.

First corrosion tests indicate that corrosion protection can be achieved with 3 nm films (Fig.5), and one may speculate that even somewhat thinner film might serve for this purpose. In one experiment, 3 nm and 4 nm ta-C coatings were deposited on sets of read/write heads. Corrosion was tested using the standard Battelle test. The Battelle test consists of 48 hours exposure at 30°C, 65% relative humidity, in the presence of 8 ppb hydrogen sulfide, 8 ppb chlorine gas, and 80 ppb nitrous oxide). The heads coated with the Twist Filter System survived the corrosion test, indicating that the 3 nm overcoats are continuous.

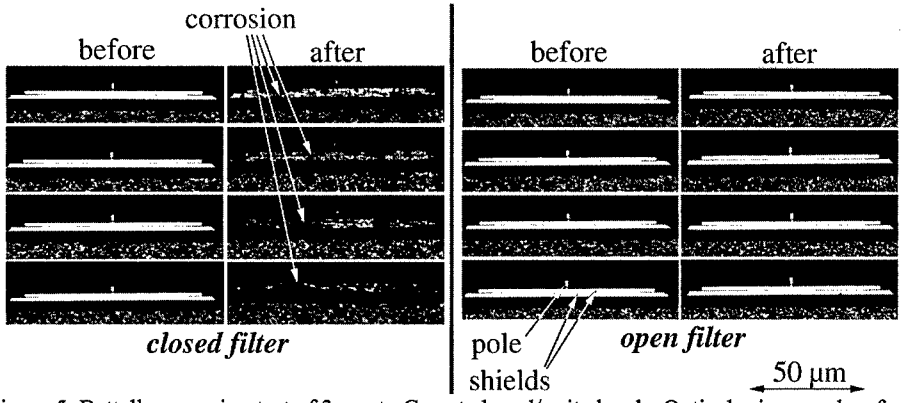


Figure 5. Battelle corrosion test of 3-nm ta-C coated read/write heads. Optical micrographs of NiFe shields before (left columns) and after (right columns) the test. The two left columns show heads that were coated using a DC carbon vacuum arc with a closed filter; and the two right columns rows show heads coated with the open Twist Filter system.

**Surface analysis by atomic force microscopy (AFM)**

Films of ta-C were deposited on <100> Si wafers using a closed filter and the Twist Filter system. Ultrathin films usually have too few particles to be quantified by AFM, therefore, relatively thick films of 40 nm were used for this study. Figure 6 shows clearly that macroparticle reflection is practically eliminated in the Twist Filter system.

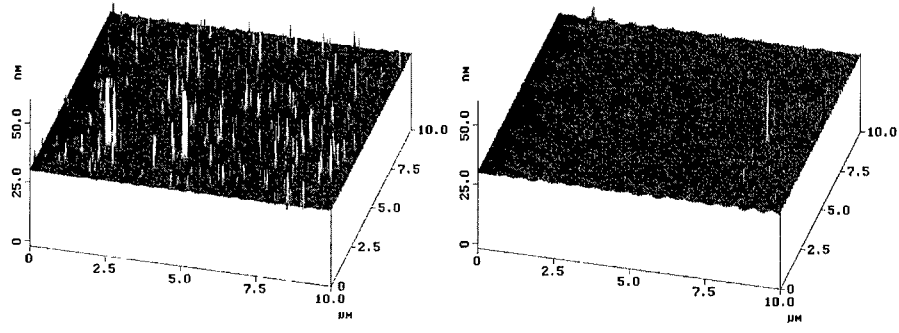


Figure 6. AFM pictures of the surfaces coated with ta-C (10 μm x 10 μm, height scale 25 nm). Left: Film of 41 nm deposited with DC-arc and closed filter. Right: Film of 40 nm deposited with a prototype Twist Filter system in a laboratory (non-cleanroom) environment.

**Hardness and elastic modulus**

Hardness and elastic modulus of filtered arc ta-C films have often been measured (see, for instance, [38]). The values reported are among the highest for the various kinds of diamondlike carbon. Peak hardness is typically 60 GPa and Elastic modulus up to 400 GPa if the average carbon ion energy is of order 100 eV, obtained by biasing the substrate. For thick (> 100

nm) ta-C films, it is known that hardness and modulus of these films have a maximum about 10-20 nm below the surface.

Nanoindentation of ultrathin films is difficult because the effect of the substrate increases with decreasing film thickness, and the indenter tip radius is much larger than the indentation depth. Other methods such as dispersion measurements of ultrasonic waves are being perfected for ultrathin films [39]. Young's modulus measurements performed this way often give greater values than nanoindentation.

To check the general quality of twist-filtered ta-C, relatively thick films of 100 nm have been deposited and measured by nanoindentation. The result is shown in Figure 7. Note that the high hardness was obtained without biasing the substrate: yet another indication that the ion energies are greater than the usually quoted 20 eV.

**Raman Spectroscopy**

Raman Spectroscopy is frequently used to "fingerprint" ta-C films by looking at the G and D peak intensities. We found that Raman spectroscopy can be used for control of deposition reproducibility, provided the deposition conditions were kept constant. Figure 8 shows Raman spectra where the targeted thickness was 3 nm and 4 nm for 3 samples each. After deposition calibration with AFM and ellipsometry, the thickness was targeted simply by counting the number of arc discharge pulses. This figure indicates that (i) ta-C films can be produced reproducibly, and (ii) Raman intensities represent a suitable signal for film control. These statements do not necessarily imply that long-term shifts do not occur and that the Raman intensity is simply proportional to thickness.

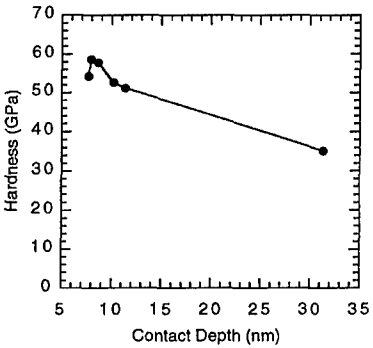


Figure 7. Hardness measurement by nanoindentation; total ta-C film thickness 100 nm.

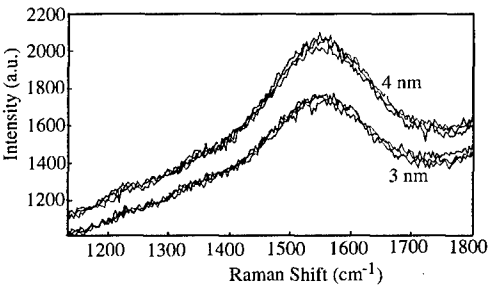


Figure 8. Raman spectra of three samples each, with targeted thickness of 3 nm and 4 nm.

**Magnetically dead layer**

The slider pole (shield) material consists of NiFe (Fe 18-22%) and the magnetoresistive element (MRE) is sandwiched between two shields. The MRE is composed of numerous materials stacked in a multilayer with copper for contacts. The iron percentage in the writer pole is much higher than in the shields (typically 50%). The primary function of the overcoat is to protect the slider poles and the MRE against corrosion. When the overcoat is applied, the surface of the magnetic multilayer is disturbed and loses its magnetic properties. Therefore, a thin

"magnetically dead" layer appears (also referred to as "magnetic dead layer"). These layers (one on the disk and one on the head) add to the magnetic spacing and hence need to be accounted for when budgeting the spacing between disk and head. The dead layer is believed to be the result of the subplantation nature of the deposition process, interface roughening, and formation of silicides at the interface if a silicon interlayer is used. Note that the deposition process with the Twist Filter system does not use a silicon interlayer.

To investigate the dead layer thickness, a layer of 20 nm NiFe (18% Fe) was coated on Si substrate. The saturated magnetic flux density $B_s$ was measured before and after ta-C deposition using a B-H looper. From the loss of $B_s$ one can calculate the approximate thickness of the dead layer. This technique was applied to ta-C films synthesized with the Twist Filter System, and the magnetically dead layer was found to be about 0.5 nm which is close to the resolution limit of the method.

**Hydrogen content**

The hydrogen content in the film was determined by Nuclear Resonance Analysis (NRA). The method is based on the nuclear reaction $^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He + \gamma$ where the $^{15}N$ ions have an energy greater than the resonant energy of 6.385 MeV. After the $^{15}N$ ions penetrate the sample surface, they lose energy, and when they reach the resonant energy at some depth, $\gamma$-rays are produced whose intensity is proportional to the hydrogen content at that depth. By measuring the $\gamma$-ray yield as a function of beam energy, the H concentration as a function of depth can be determined.

A silicon specimen deposited with a Twist Filter ta-C film of about 10 nm thickness yielded an H-concentration of 9-11%. Although this value is much lower than hydrogenated diamondlike carbon (a-C:H), the value is surprisingly high for a process that uses graphite only. Although one may question the accuracy of the measurement, there is evidence that a pulsed vacuum arc process with a strong magnetic field in a high-vacuum environment does indeed produce significant amounts of hydrogen. Schneider et al. [40, 41] have shown that residual water vapor can be efficiently ionized when a magnetic field is present. The hydrogen content in alumina films deposited by filtered cathodic arcs was found to be about 8% [42]. Interestingly, cathodic arc ta-C films made several years ago at Berkeley Lab with a 90° filter at much lower magnetic field strength showed 1-3% hydrogen content. These (unpublished) measurements were made with Elastic Recoil Spectroscopy (ERS). The difference in the results could be associated with not only possibly different vacuum base pressures but also by the degree of ionization of the water vapor due to the higher magnetic field of the Twist Filter.

## MONTE CARLO SIMULATIONS

Monte Carlo codes such as the well-known TRIM (transport of ions in matter [43]) are suitable for the determination of the mean projected range (penetration depth) and many other parameters of stopping of energetic particles in matter. TRIM was originally developed to calculate element profiles obtained by ion implantation. For the calculation of film growth one needs to use a *dynamic* version of TRIM, i.e. a version that updates the composition of the substrate by the incorporation of the arriving ions. In this work we use the dynamic TRIM version T-DYN 4.0 by Biersack [44]. One has to be careful when approaching the range of very low energy (very low energy in this context is less than 100 eV) because the interaction potential functions used in the simulation are optimized for much higher energies (usually keV to MeV). The actual interaction at very low energy is not very accurately described by the two-body

interaction functions used in the simulation. Molecular dynamics simulations (see e.g., [45]) may be a better approach but they are computationally intensive and still limited to a relatively small number of atoms. It is believed that T-DYN simulations give a correct qualitative and approximate quantitative description of films growth when using cathodic arc plasmas with ion energies greater than the displacement energy.

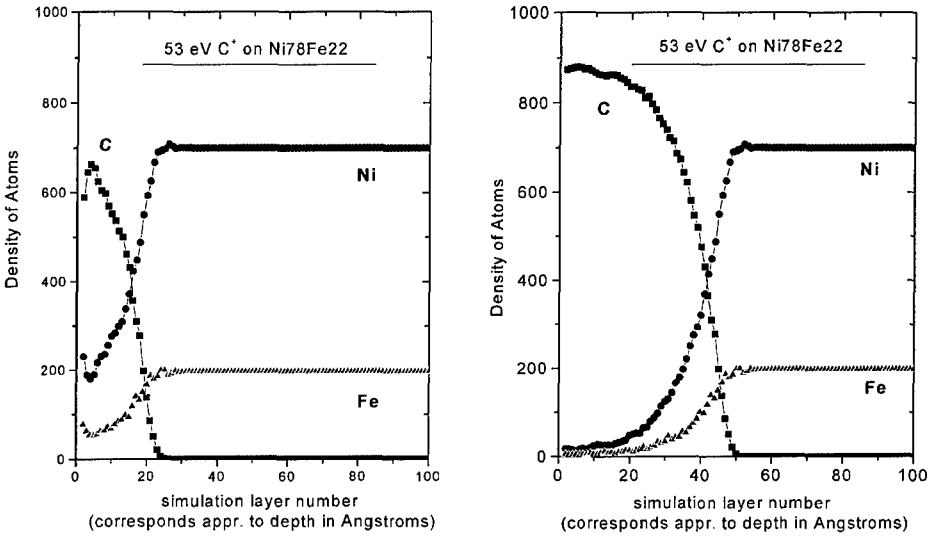


Figure 9. Dynamic TRIM simulation of carbon film growth on Ni78Fe22 alloy, assuming a carbon ion energy of 53 eV; the left figure shows the situation when a nominally 1 nm thick ta-C film is deposited (nominal 1 nm of ta-C with 2.9 g/cm$^3$); the right figure represents a continuation of the deposition to nominal 3 nm of ta-C film. The density in these figures refers to the atom number per volume of a simulation cell. Such a cell has a volume of about $10^{-20}$ cm$^3$.

Figure 9 illustrates the growth of cathodic arc ta-C film on NiFe alloy. A carbon ion energy of 53 eV was chosen based on measurements by Yushkov at al. using a similar cathodic arc system [14]. At the beginning of the deposition process, carbon ions penetrate the magnetic alloy with an average range of 0.5 nm (1 nm = 10 Å). With increasing carbon dose (i.e. deposition time or arc pulse number), the Ni and Fe concentrations decrease while the carbon concentration increases. At about 2 nm (nominal) film thickness one can actually speak of a film because the carbon concentration approaches 100%. An intermixed layer between the carbon and the metal alloy remains and it will not be changed when film growth continues because the mean projected range is less than the film depth. The intermixed layer is believed to have a beneficial effect for the adhesion of the growing ta-C film. On the other hand, this intermixed layer contributes to the magnetic spacing since one can assume that it is magnetically dead, and thus it must not be too thick. The mean projected range of 0.5 nm can be associated with a magnetically dead adhesion layer, in good agreement with experimental data for the thickness of the magnetically dead layer (see above). Note that in all of the here described experiments, no

silicon interlayer was used. Such an interlayer is conventionally applied to enhance adhesion of the carbon overcoat. The fact that a thin magnetically dead layer of ~ 0.5 nm exists in our experiments is acceptable since the need for a silicon interlayer is eliminated.

## DISCUSSION AND OUTLOOK

An interesting question is what will happen when the film thickness is further reduced in order to reach and go beyond the 100 Gbit/in$^2$. Dynamic Monte Carlo simulations indicate that thinner films (e.g. a nominal 1 nm) deposited with ions having an energy of about 50 eV are not films made exclusively from the arriving ion species but they consist of the ion species intermixed with the substrate material (Fig. 8, left). It is likely that the carbon atoms in this layer will form C-C bonds as well as C-metal bonds (carbidic bonds). One cannot exclude that a carbidic layer may serve as the protective layer, as opposed to the ta-C film, perhaps at least for certain environments. The formation and thickness of a carbidic layer depends critically on the ratio of the incident carbon ion energy to the displacement energy of the substrate material. Displacement and intermixing will occur when the carbon ion energy exceeds the displacement energy. The minimum displacement energies for Cr, Fe, Co, Ni are 28 eV, 17 eV, 22 eV, 23 eV, respectively [46], that is, about the same value as usually assumed for the kinetic energy of cathodic arc carbon ions [15]. We have used higher energies based on recent measurements for pulsed arcs [14]. Future energy measurements should be done at systems actually used for carbon deposition on magnetic layers. That is particularly important since cathodic-arc ion energies are not only material-specific but can be manipulated by the arc discharge conditions.

If the kinetic energy of carbon ions is less than the displacement energy, one can assume that a very thin carbon overcoat can be obtained that has not an intermixed layer. However, such a carbon film is likely to be graphitic because the (subplantation) growth conditions for an $sp^3$-rich phase are not fulfilled (the minimum displacement energy for graphite and diamond is 25 and 35 eV, respectively). It is likely that such film is neither continuous, nor tough, nor adherent.

Summarizing, it has been shown that 3 nm films can be deposited by advanced filtered cathodic arc deposition. It can be argued that ta-C overcoats have a principal physical limit at about 2 nm: thinner films will either not exhibit the ta-C characteristic $sp^3$-rich phase or consist of both carbon and the base metal. In the latter case, one may speculate about protection of the magnetic layer by a carbidic phase. These conclusions are based on energy arguments and therefore not limited to cathodic arc deposited films.

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